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WIND TUNNEL WALL EFFECTS.(U)  
SEP 76 J C ERICKSON, R J VIDAL

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WIND TUNNEL WALL EFFECTS.

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Project No. NR 061-199

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## I. INTRODUCTION

*This document summarizes a study of work done.* The concept of a self-correcting wind tunnel, i.e., one which uses active control of the flow by the walls in conjunction with functional relationships among measured flow disturbance quantities to insure that unconfined-flow conditions exist in the test section, was originated independently by Sears<sup>1</sup> and by Ferri.<sup>2</sup> *as applied to* An application of the concept to a two-dimensional transonic wind tunnel, has been underway at the Calspan Corporation since 1 November 1971, sponsored jointly by ONR and AFOSR, with additional support by NASA Langley Research Center, under Contract No. N00014-72-C-0102. That contract was completed on 30 September 1976, and the AFOSR and the ONR support of this research was continued under Contract No. N00014-77-C-0052. The purpose of this report is to summarize the work accomplished under the first contract and to list the reports and papers that describe the details of the research.

## II. RESEARCH RESULTS

The research has included both theoretical tasks and experimental tasks, and the status and completion of these tasks have been documented in a series of annual reports.<sup>3-7</sup> The most significant results of this research have been published as Calspan Technical Reports and as papers (most of which have been reprinted as reports). These are, in chronological order, References 1 and 8 through 12. The highlights of these efforts are summarized here, and further details of that work can be obtained in the cited references.

### Theoretical Tasks

The first of four theoretical tasks was the development of computer programs for evaluation of the functional relationships which must be satisfied by the disturbance velocity components in unconfined flow. For fully subsonic flow, a multipole expansion (MPE) technique was developed<sup>8</sup> to provide both interpolation in the measured data and evaluation of the functional relationships.

After considerable operational experience in the initial demonstration experiments,<sup>6,10</sup> certain apparent deficiencies in the MPE led us to develop<sup>6</sup> a vortex distribution method as an alternative. This method incorporates interpolation in the measured data by a cubic spline procedure. For mixed transonic flows, Dr. W.J. Rae developed<sup>4</sup> a basic program which carries out finite-difference solutions to the transonic small-disturbance equations. This program, which uses either a conventional cubic spline or a smoothed cubic spline interpolation procedure, has been generalized<sup>7</sup> to handle our experimental situation in which the two velocity components are measured at different distances from the airfoil. All of the programs have undergone continuous review and modification as required by the demands of the actual experiments.

The second theoretical task was the estimation of errors in the flow about the model when the unconfined-flow functional relationships are not satisfied exactly. This investigation, carried out for incompressible flow, used a computer program<sup>4,8</sup> which evaluated the flow field about an airfoil in a tunnel which has arbitrary distributions of either velocity component prescribed at the control surfaces. We concluded<sup>4</sup> that for low-speed flows, neither expected measurement accuracies nor up- and downstream truncation of the porous-wall test section should introduce significant errors in the final measured pressures, forces and moments on the airfoil model.

The third theoretical task was the determination of the best means of using the variable wall porosity and plenum pressure control to approach unconfined flow. To this end, a logical iteration procedure was developed<sup>8</sup> to proceed from an initial guess of the flow disturbance distributions at the control surfaces to the unconfined-flow distributions. This procedure was demonstrated in a series of numerical simulations of a self-correcting wind tunnel in both incompressible flow<sup>8</sup> and transonic flow for which shock waves extended beyond the control surface locations.<sup>4</sup>

The fourth and final theoretical task was the direct support of the experiments. Evaluation of the unconfined-flow functional relationships was the principal aspect of this task. In addition, however, flow field estimates

were made for test section design,<sup>3</sup> sensor evaluation,<sup>3,4</sup> and for use as initial approximations for beginning the experimental iterations.<sup>5,10</sup> Dr. Rae also analyzed<sup>5</sup> a turbulent wall boundary layer with blowing and suction in order to resolve discrepancies observed in some early measurements of volume flow through the wall.

#### Experimental Tasks

The experimental effort included the design and fabrication of a two-dimensional model, testing the model in the Calspan 8-Foot Wind Tunnel to obtain interference-free data, design and fabrication of a two-dimensional test section for the Calspan 1-Foot Wind Tunnel, a study of sensors for measuring flow field disturbance velocities, wind tunnel calibration experiments, and iteration experiments with the self-correcting wind tunnel.

The two-dimensional model and the 8-Foot Tunnel tests have been described and reported in Reference 9. Briefly, it is an NACA 0012 airfoil section with a 6-inch chord and a 48-inch span. It has a metric section 2-1/2 inches wide supported by a three-component strain gage balance, and an adjacent row of pressure orifices on the non-metric section. The model was tested in the 8-Foot Tunnel by mounting it on a reflection plane cart and supporting the tip with a large end plate that spanned the wind tunnel. The tests were made with a chord Reynolds number of  $10^6$ , at Mach numbers ranging from 0.4 to 0.95, and at angles of attack ranging from  $-2^\circ$  to  $+8^\circ$ .

The self-correcting test section has been described in References 1, 10 and 11. Briefly, it is a two-dimensional test section with solid side walls and porous (22-1/2%) top and bottom walls. The cross-section is 10 by 12 inches and the test section is 56 inches long. The porous walls have a total of 18 segmented plena, each of which is connected through individual control valves to an auxiliary vacuum or pressure source. The flow through the walls is controlled by pressure adjustment in each plenum. There are provisions for varying the porosity and the distribution of porosity at six of the wall segments in the immediate vicinity of the airfoil model.

A study was made of the sensor techniques available for measuring two disturbance quantities in the model flow field. The study examined non-intrusive techniques, such as the laser doppler velocimeter and measurements of the volumetric flow through the walls, and intrusive aerodynamic techniques, such as aerodynamic probes, hot wire or hot film anemometers, and gradient measurement techniques. The nonintrusive techniques were eliminated because of their complexity and their marginal sensitivities. The techniques selected were static pressure measurements using conventional static pressure pipes in the inviscid stream, and flow angle measurements using commercially-available aerodynamic probes. It was found feasible to measure static pressure with a resolution of about 0.02%, and to measure the local flow angles with a resolution of about  $0.03^\circ$ .

The wind tunnel calibration experiments consisted of running the wind tunnel with an empty test section without active wall control, and measuring the static pressure distribution on the test section centerline. These experiments showed<sup>10</sup> that when the wind tunnel was operated in this conventional mode, the Mach number varied by about 25% over the test section length. Wall control was then applied and after two iterative adjustments, this Mach number variation over the length of the test section was reduced to  $\Delta M = \pm 0.0025$ , which is comparable with many existing facilities. We have used this mode of operation to simulate a conventional wind tunnel. That is, wall control is used to obtain a uniform longitudinal distribution of static pressure in the empty tunnel. The model is then installed and the tunnel is operated with the same valve settings for the wall control.

We have tested the 6-inch chord model in the 12-inch high test section (6% blockage area) simulating a conventional facility and have shown that the wall interference effects are large.<sup>10,12</sup> For example, at  $M_\infty = 0.725$  and  $\alpha = 2^\circ$ , the interference effects on lift, drag and pitching moment are 25%, 130% and 75%, respectively, and the shock wave is displaced about 15% of the chord aft of the interference-free location.

We have successfully iterated two test conditions,  $M_\infty = 0.55$  and  $\alpha = 6^\circ$ , and  $M_\infty = 0.725$  and  $\alpha = 2^\circ$ . In both examples, there is a shock wave on the airfoil but it does not extend to the walls. We performed six iterations at the first test condition, to obtain theoretical convergence; i.e., the discrepancies between the measurements and the functional-relationship evaluations were comparable with the measurement resolution. The measured airfoil pressure distribution was in good agreement with the data from the 8-Foot Tunnel tests, but equally good agreement was also observed after the second or third iteration. The implication is that our criterion for theoretical convergence might be too stringent. We performed three iterations at  $M_\infty = 0.725$  and  $\alpha = 2^\circ$  but had to terminate those iterations because the wall control was inadequate. After the third iteration, the lift and drag agreed with the 8-Foot Tunnel data within the repeatability of that data, and the discrepancy in the pitching moment data was less than 10%.

Under Contract No. N00014-77-C-0052, development of the self-correcting tunnel concept is continuing. Principal emphasis is on the higher Mach numbers, especially those cases where the shock wave extends beyond the wall location.

#### IV. PAPERS AND LECTURES

The following is a complete list of papers and lectures presented during this contract period.

Sears, W.R.: "Self-Correcting Wind Tunnels". The Sixteenth F.W. Lanchester Memorial Lecture, Royal Aeronautical Society, London, 3 May 1973.

Sears, W.R.: "Workshop Meeting on Transonic Wall Interference Effects". NASA Langley Research Center, 29-30 May 1974.

Ritter, A.: "The Self-Correcting Wind Tunnel Program at Calspan Corporation". AGARD MiniLaWs Working Group on Design of Transonic Working Sections, AEDC, 11-12 July 1974.

Erickson, J.C., Jr.: "The Concept of a Self-Correcting Wind Tunnel". 42nd Semi-Annual Meeting of the Supersonic Tunnel Association, Calspan, 1-2 October 1974.

Vidal, R.J.: "Experiments With a Self-Correcting Wind Tunnel". 42nd Semi-Annual Meeting of the Supersonic Tunnel Association, Calspan, 1-2 October 1974.

Vidal, R.J., Erickson, J.C., Jr. and Catlin, P.A.: "Experiments With a Self-Correcting Wind Tunnel". AGARD Symposium on Wind Tunnel Design and Testing Techniques, London, 6 October 1975.

Vidal, R.J.: Western Atlantic Working Group on Design of Transonic Working Sections (AGARD MiniLaWs), Calspan, 24-25 February 1976.

Sears, W.R.: "Experience with an Adaptive Wall Wind Tunnel". ONR Conference on Transonic Flows, UCLA, 30-31 March 1976.

Wittliff, C.E.: "Space Shuttle Tests in the Shock Tunnels and Experiments with an Adaptive-Wall Wind Tunnel". 45th Semi-Annual Meeting of the Supersonic Tunnel Association, Albuquerque, 13-14 April 1976.

Sears, W.R.: "Modern Developments in Wind Tunnel Testing". Biennial Invited Lecture in honor of Dr. Theodore von Karman, 18th Annual Conference for the Israel Society for Aeronautics and Astronautics, 19 May 1976.

Sears, W.R.: "Some Experiences With the Exploitation of Measurements of the Perturbation Field in a Wind Tunnel to Improve Simulation". AGARD Conference on Numerical Methods and Wind Tunnel Testing, Von Karman Institute for Fluid Dynamics, Rhode-St.-Genese, Belgium, 23-24 June 1976.

Sears, W.R., Vidal, R.J., Erickson, J.C., Jr., and Ritter, A.: "Interference-Free Wind Tunnel Flows by Adaptive-Wall Technology". Tenth Congress of the International Council of the Aeronautical Sciences. Ottawa, Canada, 3-8 October 1976.

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3. Erickson, J.C., Jr. and Vidal, R.J.: "Wind Tunnel Wall Effects", Annual Progress Report, 15 November 1971 to 15 November 1972, Contract No. N00014-72-C-0102.
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9. Vidal, R.J., Catlin, P.A. and Chudyk, D.W.: "Two-Dimensional Subsonic Experiments with an NACA 0012 Airfoil", Calspan Report No. RK-5070-A-3, December 1973.
10. Vidal, R.J., Erickson, J.C., Jr. and Catlin, P.A.: "Experiments with a Self-Correcting Wind Tunnel", Paper No. 11, AGARD Conference Proceedings No. 174 on Windtunnel Design and Testing Techniques (London, England), 6-8 October 1975; also Calspan Report No. RK-5070-A-4, October 1975.
11. Sears, W.R.: "Some Experiences With the Exploitation of Measurements of the Perturbation Field in a Wind Tunnel to Improve Simulation", AGARD Conference on Numerical Methods and Windtunnel Testing, AGARD CP-210, June 1976.

12.     Sears, W.R., Vidal, R.J., Erickson, J.C., Jr. and Ritter, A.: "Interference-Free Wind-Tunnel Flows by Adaptive-Wall Technology", ICAS Paper No. 76-02, Tenth Congress of the International Council of the Aeronautical Sciences, Ottawa, Canada, 3-8 October 1976; also Calspan Report No. RK-6040-A-1, January 1977.